

Annual Progress Report

10/99 to 7/00

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**Title of Research Grant: Use of ARM Data for Understanding and Parameterizing
Cloud and Aerosol Forcing in GCMs**

Scientific Goals:

The fundamental scientific goal of our research is to use ARM observations at the SGP and TWP sites to understand cloud properties and use these and other properties to address pressing issues in the evaluation and development of convection and cloud parameterizations in GCMs. Toward this goal, we use the following research tools that we have developed: 1) *3-D multi-spectral Monte Carlo radiative transfer model*, 2) *convective parameterization scheme in the NCAR CCM3*, 3) *satellite retrieval scheme* and 4) *Lagrangian cloud classification algorithm*. The objectives of our research are:

1. Evaluate and improve GCM treatments of convection and clouds using ARM SGP observations.
2. Understand cloud and aerosol radiative interactions over ARM sites and its implications to GCM parameterization.

Specific Accomplishments:

- Marked improvement of the convective parameterization in the NCAR CCM3 using the ARM IOP observations at the SGP site.
- Developed and tested a new cirrus cloud parameterization in the NCAR CCM3.
- Determined 3-D solar radiative heating rates in clouds over the TWP, their dominant factors, and identified GCM biases in heating rates.
- To help put the ARM TWP site observations in large-scale perspective, we determined the heat balance in the warm pool atmosphere.
- Validated the databases of spectroscopic line parameters and the extraterrestrial solar source function at 1 cm^{-1} resolution from 0.4 to $1.11\text{ }\mu\text{m}$.
- Developed two complementary methods for observationally determining aerosol radiative forcing directly from surface radiometric observations.

Progress and Accomplishments during the Last Twelve Months

1. GCM treatments of convection and clouds using ARM SGP observations.

a. Convective parameterization studies (Zhang)

Based on the knowledge we gained from comparing the model simulations with the observations at the ARM SGP site, we modified the Zhang and McFarlane (1995) convection scheme, which has been used in the standard NCAR CCM3, to improve the model simulation. Surface observations during the Single Column Model (SCM) IOPs at the ARM SGP site indicate that significant precipitation occurs only when large-scale conditions are favorable. On the other hand, the simulated precipitation in CCM3 SCM occurs too often, and is overly dominated by the diurnal cycle, which is apparently related to the surface diurnal heating. This problem is due to the fact that the original Zhang-McFarlane convection scheme uses convective available potential energy (CAPE) to close the parameterization. Since CAPE is dominated by the thermal properties of the near surface air, the original closure for convection over-emphasizes the role of boundary layer air and in essence decouples convection from the large-scale forcing. Consequently, we revised the convection scheme to couple convection to the large-scale forcing in the free troposphere, instead of to the existing convective instability.

We tested the revised scheme in both the single column model version and the full GCM version of CCM3. The single column model tests for both the SCM IOPs at the ARM SGP site as well as in the tropics show that the simulation of precipitation is now in excellent agreement with the observations (Fig. 1). The simulated temperature and moisture fields are also significantly improved (Fig. 2). The full GCM simulations are performed over the TOGA COARE period and for a 5-yr time period. Note that a well-known weakness in the standard CCM3 is the lack of temporal variability in its climate simulation, particularly on intraseasonal timescales such as Madden-Julian Oscillations. The model using the revised scheme simulates the observed Madden-Julian Oscillations and the associated westerly wind bursts well. The long-term integration of CCM3 further demonstrates that the temporal variability on intraseasonal timescales is well simulated. We attribute the improved simulation of the temporal variability to the more faithful representation of the interaction between convection and the large-scale fields in the revised convection scheme (Zhang 2000a,b).

b. Cirrus cloud parameterization (Zurovac-Jevtic, Zhang and Ramanathan)

As an integral part of our effort to improve cloud parameterization using ARM observations, we undertake the task to develop and test a cirrus cloud parameterization in the CCM3. The ice water content (IWC) within the cirrus cloud is predicted using a combination of the parameterization of ice microphysical processes with empirical relationships for the ice crystal size spectrum. The IWC and the corresponding effective radius are then used in radiative transfer calculations.

We have evaluated the effects of the new cirrus scheme in the NCAR CCM3 by comparing the simulated monthly means of cirrus cover and IWC with the observations for spring 1993 in the tropical Western Pacific. Preliminary results show that cirrus cloud cover decreased from around 90% in the warm pool region by the standard CCM3 to around 45% at approximately 11 km and decreased by 10-20% at 13 km. Since the standard CCM3 produces

too much high clouds, this change represents a significant improvement. The mean IWC is increased by around 50% compared with the standard version. When the mean ice precipitation is added to IWC the total condensate is three times higher on average and compares much better with the in-situ observations during CEPEX. We will further test it in the CCM3 single column model and compare with the SGP observations.

Warm Pool Energy Budget (Tian, Zhang, and Ramanathan)

A fundamental significance of the ARM TWP site is to link the warm pool radiation budget with the total energy budget of the warm pool (WP) atmosphere. To help place the observations from the TWP site in the large-scale perspective, we use a high-resolution analysis dataset to study the role of the large-scale atmospheric circulation in the warm pool atmospheric energy balance. We found that the large-scale atmospheric circulation exports about 180 Wm^{-2} energy out of the WP atmosphere, which is equivalent to an average cooling rate of about 1.8 K/day in the whole troposphere. Thus, the large-scale heat transport is very efficient in cooling the atmosphere compared to the radiative cooling of about 0.4 K/day (Tian et al. 2000).

2. Cloud and aerosol radiative interactions over ARM sites and its implications to GCM parameterization.

a. 3-D Cloud Solar Heating Rates (Vogelmann, Ramanathan)

We have examined 3-D solar radiative heating rates within tropical convective-cirrus systems within the Tropical Western Pacific to identify the scales that contribute significantly to the spatial average over a climate model's grid cell (i.e., its grid-mean), and determine their relationship to the cloud field properties such as cloud-top height variation (Vogelmann et al. 1999, 2000a-d). These results are used to understand the spatial resolution and subgrid-scale cloud property information needed in climate models to accurately simulate the grid-mean solar heating of these systems.

The 3-D heating rates are computed by a multi-spectral Monte Carlo model for several regional-scale cloud fields ($[400 \text{ km}]^2$) whose properties are retrieved from satellite data using an algorithm we constructed. Our analyses have identified two key subgrid-scale features within these systems that largely govern the grid-mean heating rates: the variability in the cloud-top height, and the structure of the cloud edge. These features give rise to hot spots—regions of intense local heating that occupy a small area but dominate the grid-mean value. For example for the fields considered, 5 to 25% of the grid area can contribute 30 to 60% of the total heating rate, respectively. Explicitly resolving the hot spots requires a model grid of about $(20 \text{ km})^2$ to $(30 \text{ km})^2$, which is smaller than that currently used in general circulation models (GCMs) for weather forecasting and about a factor of 20 smaller than that used for climate studies. We show that, unless a grid of $\sim(20 \text{ km})^2$ is used, GCM-style heating rate calculations that employ a standard cloud overlap type treatment can significantly overestimate the solar heating aloft and underestimate it below (Fig. 3). This might enhance the vertical velocity within the cloud layer and suppress it at cloud base. Thus, over the long-term, biases in the GCM treatments of the vertical heating rate might have consequences to cloud evolution and feedback.

b. Validation of Atmospheric Absorption and Solar Emission (Vogelmann, Ramanathan)

We validated the databases of spectroscopic line parameters and the extraterrestrial solar source function using a high-resolution spectrum (1 cm^{-1}) which spans $0.4\text{--}1.11\text{ }\mu\text{m}$ (Lubin et al. 2000). The transmission spectrum computed from LBLRTM was compared to that observed using a Fourier transform infrared (FTIR) spectrometer. This intercomparison revealed that the Kurucz extraterrestrial solar irradiance spectrum contains 266 solar absorption features that do not appear in the data, resulting in an excess of $\sim 1.92\text{ Wm}^{-2}$ in the model's solar constant. Ninety seven absorption features appear in the data that do not appear in the HITRAN-96 line parameter database as used by LBLRTM, resulting in a model underestimate of shortwave absorption of $\sim 0.23\text{ Wm}^{-2}$ for a solar zenith angle of 42° . The small discrepancies revealed in this intercomparison indicate that current extraterrestrial solar irradiance models and spectroscopic databases used by shortwave atmospheric radiative transfer models are nearly entirely complete for the purposes of atmospheric energy balance calculations. Thus, clear or cloudy sky excess absorption is unlikely to be related to an incomplete identification of atmospheric absorbing gases and their spectroscopic features (at 1 cm^{-1} resolution) for a clean atmosphere of normal composition.

c. Aerosol Radiative Forcing (Ramanathan, Conant, Vogelmann)

In order to understand the impact of natural and anthropogenic aerosols on our climate, we must first accurately quantify their radiative effect on the Earth's energy balance. We have developed two complementary methods for observationally determining aerosol radiative forcing directly from surface radiometric observations (Conant 2000a,b; Conant and Ramanathan 2000a,b). These methods are the basis for an intercomparison that we have begun of the radiative impact of aerosols at the surface and top of atmosphere. Our objective for the intercomparison is to determine the variability that exists in the aerosol forcing in diverse geographical regions, and between natural and anthropogenic sources. We derive the aerosol forcing from observations obtained from the SGP and TWP sites, as well as from the Indian Ocean Experiment (INDOEX). Because the forcing is a function of the surface albedo and day length, a method must be devised that permits comparison between dissimilar locations. Preliminary results for a first-order normalization procedure suggests that SGP forcing might be similar to the predominately anthropogenic forcing found in INDOEX (Vogelmann et al. 2000e). However, a more definite assessment will be possible when we have completed developing a more robust procedure.

Planned Research

First Attempt for Integration of ARM data for Clouds, Aerosols and Water Vapor for Determination of 3-D Radiative Heating Rates (Vogelmann, Ramanathan)

We will complete the study (described earlier) that observationally determines the aerosol radiative forcing from natural and anthropogenic sources in diverse geographical regions (SGP, TWP, and INDOEX). This work will set the stage for the next phase of the research.

The dominant emphasis within our community has been on determining the radiative fluxes at the surface and at the top of the atmosphere. However, climate and general circulation are driven by the heating rate profile, and it is essential that ARM start developing methods for determining heating rate profiles from observations. There is no method for directly measuring the heating rate, thus it must be determined by integrating multiple data streams/platforms with model calculations. Fortunately, one of the unique aspects of the observations at the SGP is the high resolution time series of the data streams (point measurements) coincident with pixel-scale satellite products (2-D coverage). We will make the first attempt to integrate these observations to obtain an estimate of the 3-D atmospheric state of clouds, water vapor and aerosols from which the heating rates and their sub-grid scale variability may be computed. Specifically, we will:

- 1) Integrate multi-parameter ARM datasets into estimates of the 3-D atmospheric state;
- 2) Use these data fields to compute the 3-D heating rates in clear and cloudy scenes;
- 3) Validate GCM parameterizations of heating rates.

The 3-D distribution of cloud, water vapor and aerosol within the area of the GCM grid cell surrounding the SGP will be generated using ARM products that include those from the Raman lidar, MFRSR, MWR, cloud radar, AOS, aircraft aerosol measurements, and satellite retrievals. The solar heating rate calculations will be made at the pixel resolution using our multi-spectral Monte Carlo model. The model calculations will be validated at the surface using the radiometer data, and at the top of the atmosphere using Terra CERES data. These data will provide an essential constraint on the column energy balance. The 3-D heating rates and their variation will provide a baseline for comparison with models. Specifically, we will use these calculations to validate the corresponding calculations by the NCAR CSM radiation code, and we will make the fields available to the SCM working group for their validation purposes.

Convection and cirrus/anvil cloud parameterizations using SGP site observations (Zhang, Zurovac-Jevtic, Ramanathan, Tian, Wilcox)

We will use the ARM data and the CCM3 single column model to test and improve convection and cloud parameterization schemes. Our objectives are to:

1. Evaluate the parameterization of cirrus cloud ice water content and associated radiative properties using ARM observations at the SGP site.
2. Determine the radiative forcing of the parameterized convection and cirrus/anvil clouds, and compare it with the observations at the SGP site.
3. Understand the role of convective detrainment of hydrometeor in determining cirrus/anvil cover and ice water content.

To accomplish these objectives, we will first couple the revised Zhang-McFarlane convection scheme with the cirrus parameterization scheme in the CCM3 single column model. We will use the observed cloud fraction and ice water content from the SCM IOPs at the SGP site to validate the simulation of cirrus cloud and its ice water content for the IOP cases. The contribution to cirrus/anvil ice water content from convective detrainment of hydrometeor will be determined by considering the convective detrainment as a source for cirrus ice water calculation. Since the parameterized ice water content is used in the radiative transfer calculation, cirrus parameterization directly affects the radiative energy budget at the top of atmosphere and the surface. We will determine the sensitivity of the simulated radiative budget to convection and cirrus/anvil cloud parameterization and compare it with the observations at the SGP site.

List of Publications for 1999-2000

Peer reviewed papers:

- Conant, W. C., 2000a: An Observational Approach for Determining Aerosol Surface Radiative Forcing: Results from the First Field Phase of INDOEX. *J. Geophys. Res.*, **105**, 15,347-15,360.
- Lubin, D., A. M. Vogelmann, P. J. Lehr, A. Kressin, J. Ehramjian, and V. Ramanathan, 2000: Validation of visible/near-IR atmospheric absorption and solar emission spectroscopic models at 1 cm⁻¹ resolution. *J. Geophys. Res.* (in press).
- Tian, B., G. J. Zhang, and V. Ramanathan, 2000: On the heat balance of the Pacific warm pool atmosphere during TOGA COARE and CEPEX. *J. Climate* (in press).
- Vogelmann, A. M., V. Ramanathan, and I. A. Podgorny, 2000a: Scale Dependence of Solar Heating Rates in Convective Cloud Systems with Implications to General Circulation Models. *J. Climate* (submitted, revised).
- Zhang, G. J., D. Zurovac-Jevtic, and E. Boer, 1999: Spatial characteristics of the tropical cloud systems: comparison between model simulation and satellite observations. *Tellus*, **51A**, 922-936.
- Zhang, G. J., 2000a: Improving convective parameterization in NCAR CCM3 using observations. *J. Climate* (submitted).

Thesis:

- Conant, W. C., 2000b: Interactions between Aerosol, Water Vapor, and Solar Radiation. Ph.D. Dissertation, University of California, San Diego, 198 pp. [Available from Center for Clouds, Chemistry and Climate, University of California, San Diego, La Jolla, CA 92093-0239.]

Conference Proceedings & Presentations:

- Conant, W. C., and V. Ramanathan, 2000a: Agreement between modeled and observed 400-700 nm global and diffuse irradiance during INDOEX. Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, San Antonio, TX.
- Conant, W. C., and V. Ramanathan, 2000b: Observations of Surface Aerosol Forcing During the Asian Winter Monsoon. Proceedings of the AGU 2000. Spring meeting, Eos, 81, S122.
- Tian, B., G. J. Zhang, and V. Ramanathan, 1999: On the heat balance in the warm pool atmosphere. American Geophysical Union. Dec. 13-17, 1999. San Francisco, CA.
- Vogelmann, A. M., V. Ramanathan, and I. A. Podgorny, 1999: Scale dependence of solar heating rates in cloudy skies—Relating subgrid-scale cloud variability to GCM grid-average properties. Presented at the Atmospheric Radiation Measurement Program (ARM) Instantaneous Radiation Flux Workshop, October 11-13, Albany, NY.
- Vogelmann, A. M., V. Ramanathan, and I. A. Podgorny, 2000b: Scale Dependence of Solar Radiative Heating Rates in Tropical-Convective Cloud Systems with Implications to General Circulation Models. Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, San Antonio, TX.
- Vogelmann, A. M., V. Ramanathan, and I. A. Podgorny, 2000c: Scale Dependence of Solar Heating Rates in Convective Cloud Systems with Implications to General Circulation Models. Presented at the Gordon Conference on Solar Radiation and Climate, June 25-29, Connecticut College, Connecticut.

- Vogelmann, A. M., V. Ramanathan, and I. A. Podgorny, 2000d: Scale Dependence of Solar Radiative Heating Rates in Tropical-Convective Cloud Systems with Implications to General Circulation Models. Presented at the International Radiation Symposium, July 24-29, Saint-Petersburg State University, St. Petersburg, Russia.
- Vogelmann, A.M., V. Ramanathan, and S. K. Satheesh, 2000e: Aerosol Forcing from the Indian Ocean Experiment and the ARM-SGP. Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, San Antonio, TX.
- Zhang, G. J., 2000b: Modifications to Zhang-McFarlane convection scheme and their effects on CCM3 simulations. NCAR Climate Systems Model Workshop, June 26-29, 2000. Breckenridge, CO.
- Zhang, G. J., 2000c: Cloud properties in the ARM SGP site and their relations to the meteorological conditions. Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, San Antonio, TX.

Update on Previously Submitted Refereed Publications:

- Roca, R., and V. Ramanathan, 2000: Scale dependence of monsoonal convective systems over the Indian Ocean. *J. Climate*, **13**, 1286-1298 (From accepted).
- Zhang, G. J., D. Zurovac-Jevtic, and E. Boer, 1999: Spatial characteristics of the tropical cloud systems: comparison between model simulation and satellite observations, *Tellus*, **51A**, 922-936 (From in press).

**Single Column Model Simulations over ARM SGP Site:
Impact of ARM SGP Data on GCM Convection Parameterization**

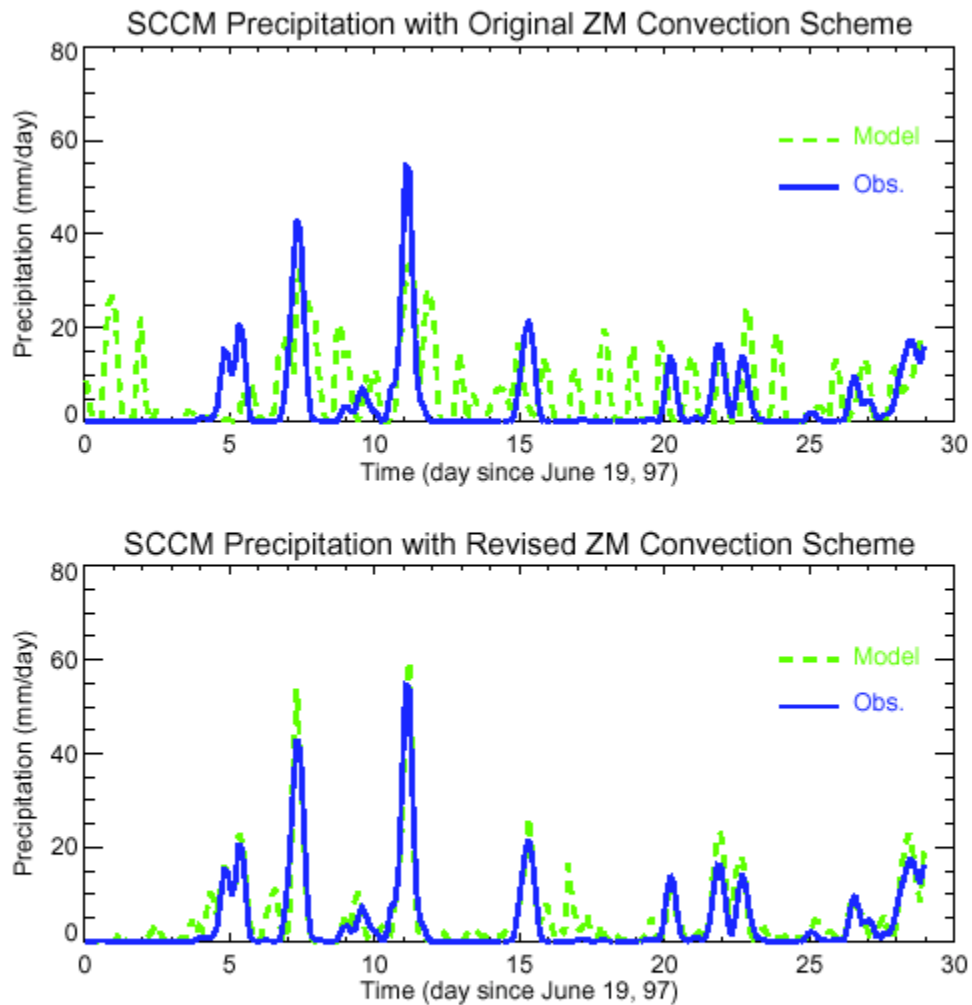


Fig. 1: Simulated surface rainfall at the SGP site by NCAR CCM3 single column model with the original convection scheme (upper panel), and the improved scheme that was formulated based on the ARM observations (lower panel).

Provided by Guang Zhang, Scripps Institution of Oceanography, July 2000.

**Single Column Model Simulations over ARM SGP Site:
Impact of ARM SGP Data on GCM Convection Parameterization**

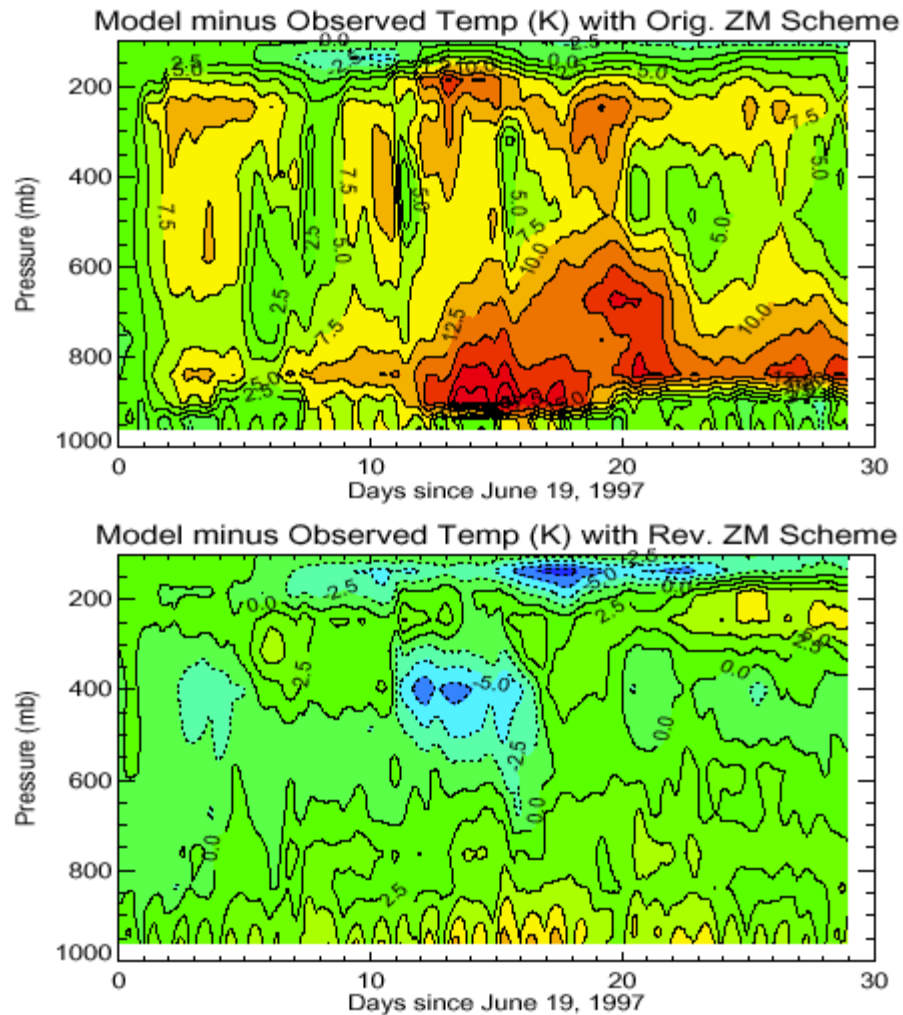


Fig. 2: Biases in the simulated temperature field at the SGP site by NCAR CCM3 single column model with the original convection scheme (upper panel), and the improved scheme that was formulated based on the ARM observations (lower panel). Contour intervals are 2.5 K. Note that the biases in the upper panel are often more than 10 K whereas those in the lower panel are mostly within ± 5 K.

Provided by Guang Zhang, Scripps Institution of Oceanography, July 2000.

SCALE-DEPENDENT BIASES IN GCM COLUMN AVERAGE SOLAR HEATING RATES

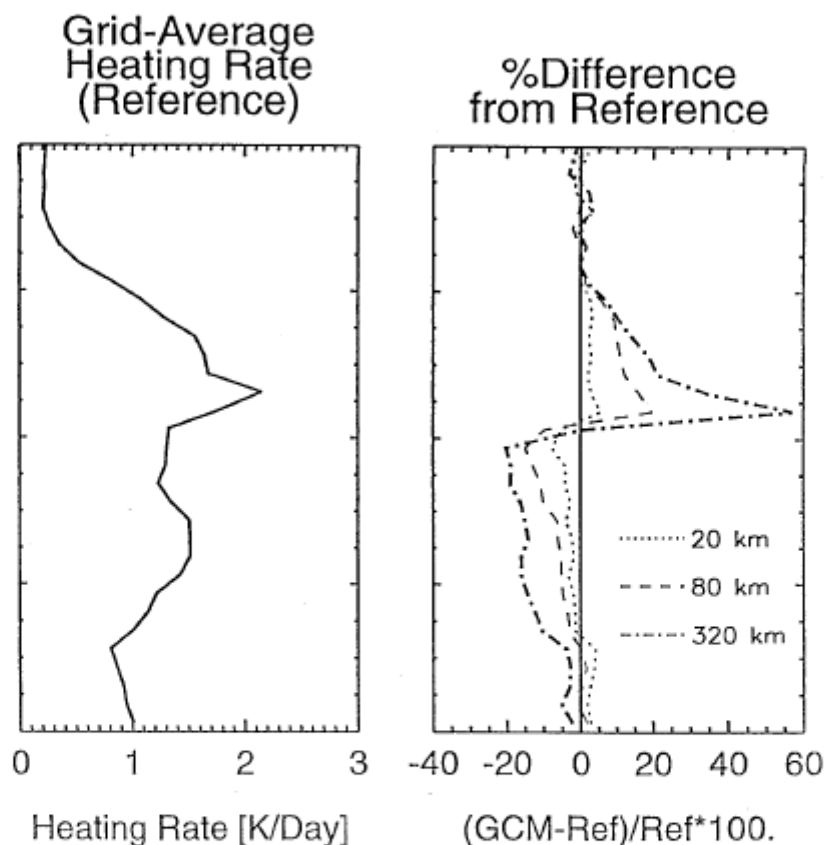


Fig. 3. Percentage difference of the grid-mean heating rates for varying GCM resolutions. Cloud properties on a high resolution grid ($[5 \text{ km}]^2$) are systematically degraded while employing a standard type of GCM cloud overlap assumption. The objective is to determine the largest scale for which the overlap treatment can simulate heating rates comparable to the reference case. The reference case uses the full resolution of the cloud inputs (i.e., $[5 \text{ km}]^2$ with no horizontal averaging), and 320 km (i.e., $[320 \text{ km}]^2$) represents the results for a typical GCM treatment at T42 resolution. Results indicate that significant errors may result for grid sizes larger than $(20 \text{ km})^2$.

From Vogelmann et al. (2000a)